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Experimental and theoretical investigations on stimulated Brillouin scattering (SBS) in multimode fibers, at 1550 nm wavelength

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ABSTRACT

The main goal of this paper is the study of the stimulated Brillouin scattering (SBS) in multimode fibers, at 1550 nm wavelength, cw operation, in order to build high power IR fiber lasers. Two theoretical models are considered, the usual plane wave model and a modal model, developed in this paper. The theoretical results for SBS threshold and SBS reflectivity are compared with the experimentally determined values. Good agreement was obtained when using the mode structure analysis.

Keywords: Stimulated Brillouin scattering,, cw, fiber optics, reflectivity.

1. INTRODUCTION

The nonlinear process of SBS, first observed in 1964, has been studied extensively[1]. The use of fibers as nonlinear media for generation of SBS, besides other advantages, reduces drastically the SBS threshold. The extension of this to multimode fibers opened the possibility of realizing near diffraction limited output from a cw[2] or high repetition frequency pulsed high power solid state laser[3].

Since their invention in 1985, erbium doped fiber amplifiers (EDFAs)[4] have attracted great interest, principally because of their large commercial potential in the field of optical communications, since their operating wavelength coincides with the third window for optical fiber communications near 1550 nm. However, the uses of EDFA's have not been confined to telecommunications, and there has been steadily growing interest in for example, the amplification of pulses to provide a source of very high peak power.

SBS appears to be a very attractive mechanism for use in new schemes for efficient beam combining to obtain very high power from fiber lasers, and is the primary motivation for the present study.

Previous reports on SBS in fibers have described conflicting results, notably with regard to SBS thresholds[2]. We have measured the SBS threshold in a multimode fiber and found it to be in agreement with the measurement of Ref. 2, which is approximately a factor of four lower than that predicted by the plane wave theory of SBS generated from noise[5]. In the plane wave model, the SBS threshold is given by the well known formula $P_{thres} = 21 A_{eff}/gL_{eff}$, where A_{eff} is the effective core area, g is the Brillouin gain, and $L_{eff} = [1-\exp(-\alpha L)]/\alpha$, where L is the length of the fiber. The authors of Ref. 2 have proposed that the lowering of the threshold could be caused by retro-reflection of a portion of the pump radiation by the transversely-cleaved far end of the fiber; however, in our experiments, the far end of the fiber was angle-cleaved, so that reflection of light from the end of the fiber was circumvented.

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We have focused on the launching conditions on SBS in multimode fibers by analyzing the mode structure and found in this way, a good agreement between experiment and theory for the SBS threshold and SBS reflectivity.

2. EXPERIMENTAL SET UP

The block diagram of the experimental set up is shown in Fig.1. We have used a master oscillator-power amplifier configuration (MOPA) to generate SBS in a multimode fiber. A tunable narrowband (150 kHz) semiconductor laser (Santec TSL 210) was used as a master oscillator for generation of radiation at 1550 nm. Two amplification stages (JDS Uniphase and Keopsys EDFAs, respectively) were used to amplify the small signal from the oscillator (2 mW) up to the watt level (the maximum output power from the Keopsys amplifier was 5 W). We used isolators in order to avoid feedback into the oscillator and amplifiers. A circulator was used to separate the input and the SBS return from the multimode fiber. The whole pumping configuration is based on single mode fiber (core diameter = 8 μm, cladding diameter = 125 μm). The coupling between the single mode fiber and the multimode fiber is made using a FC/APC connector and we called this type of coupling "butt coupling". The multimode fiber was a step-index silica fiber (Corning) with a core diameter of 50 μm, cladding diameter 125 μm, and length 4.4 km.

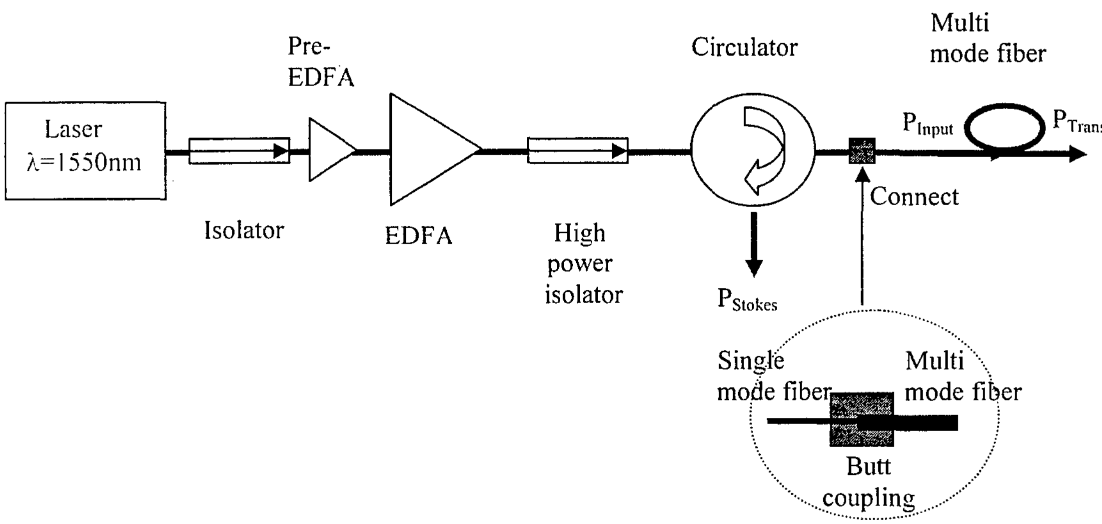

Fig. 1 Schematic diagram of the experimental set up for SBS in multimode fibers

3. THEORETICAL MODEL

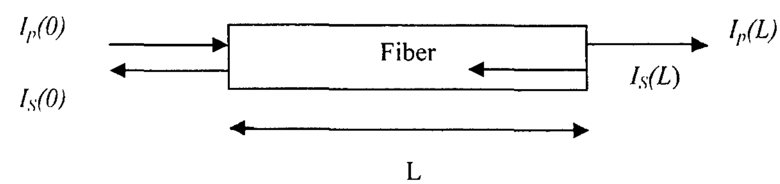

Fig. 2 Schematic used to model the SBS interaction in the fiber

The plane wave model applied for the SBS process generated from noise, gives, under steady state conditions (appropriate for CW pumping), the following system of equations (in the absence of fiber losses) :

$$\frac{dI_S}{dz} = -gI_S I_p$$
$$\frac{dI_p}{dz} = -gI_S I_p \tag{1}$$

where I_S, I_p are the intensities of the Stokes and the pump radiation, and z is the coordinate along the direction of propagation in the fiber.
From Eq. (1) it follows that the condition between the two intensities is (where C is a constant) :

$$I_p(z) - I_S(z) = C \tag{2}$$

The SBS reflectivity is defined as :

$$R_{SBS} = \frac{I_S(0)}{I_p(0)} \tag{3}$$

By using the threshold condition for SBS[5]: $gL_{eff} I_p(0) = 21$ where g is the Brillouin gain, L_{eff} is the effective length of the fiber, and $I_p(0)$ the initial input intensity, the SBS reflectivity was calculated by solving the equation :

$$\frac{R_{SBS}(1-R_{SBS})}{\exp\left[gL_e I_p(0)(1-R_{SBS})\right]} = \exp(-21) \tag{4}$$

where $I_p(0) = \frac{P(0)}{A_{eff}}$ and A_{eff} is the effective core area of the multimode fiber.

However, doing so leads to disagreement with experimental measurements for the SBS threshold and SBS reflectivity. To correct this, we compute an effective modal area $\left(\pi\overline{r^2}\right)$ by calculating the number of modes excited in the multimode fiber (SBS medium) by the input field of the single-mode fiber.

We assume that the electric field in the single mode fiber is represented by a Gaussian given by :

$$E = A\Psi(r) = A\exp(-r^2 / w^2) \tag{5}$$

For circularly symmetric weakly guided fiber there is no azimuthal dependence and the multimode fiber electric field is given by the sum of eigenfunctions :

$$E^m = \sum_{n=0}^{M} A_n \Psi_n(r) \tag{6}$$

The eigenfunctions are :

$$\Psi_n(r) = L_n(\beta r^2)\exp\left(-\frac{\beta r^2}{2}\right) \tag{7}$$

where β is the multimode parameter, $\beta = V / a^2$; V is the normalized frequency of the fiber[5], a is the fiber core radius, and L_n are the Laguerre polynomials of radial order n.
The amplitudes A_i are found by projection on the eigenfunctions and are :

$$A_i = A\frac{\int_0^\infty \Psi_i(r)^* \Psi(r) 2\pi r dr}{\int_0^\infty \Psi_i(r)\Psi_i(r) 2\pi r dr} \tag{8}$$

The fractional power in the i-th mode is given by $|A_i|^2$.

From eq. (8) one can calculate the effective area for all modes excited in the multimode fiber by the input field E, $\left(\pi\overline{r^2}\right)$:

$$\pi\overline{r^2} = \pi\frac{\sum A_i A_j^* \int_0^\infty \Psi_i(r)^* \Psi_j(r) r dr}{\sum A_i A_i^* \int_0^\infty \Psi_i(r)^* \Psi_i(r) r dr} \tag{9}$$

4. M² MEASUREMENTS (KNIFE EDGE METHOD) AND CALCULATION OF THE SPOT SIZE AT THE SINGLE MODE FIBER FACE

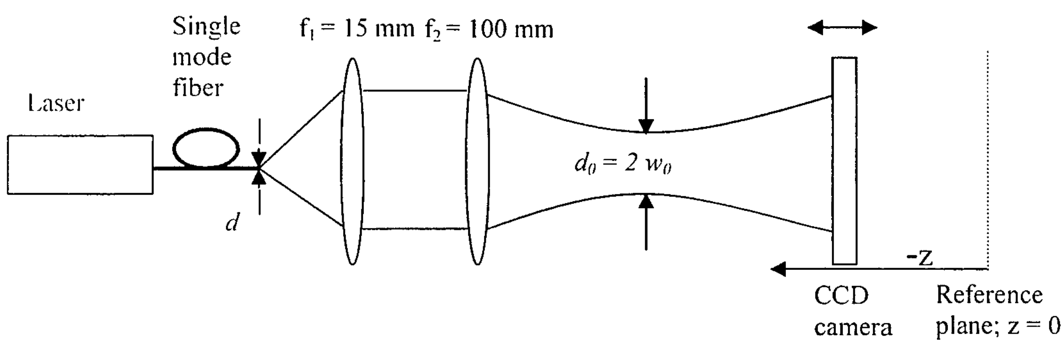

Fig. 3 Experimental set up for measuring the beam quality (M^2)

An electronically-controlled translation stage driving the knife edge and the Coherent Beam View Analyzer software were used to determine the beam diameter in different positions on both sides of the beam waist. The distance (Δx or Δy) between the positions for 84% and 16% transmitted power determines a beam radius w_e which is equal to the second moment beam radius in the case of a Gaussian beam (ISO 11146:1999). The beam propagation properties were estimated using a parabolic fit for the square of the beam radius as a function of the longitudinal coordinate z.

$$w_e^2 = A + Bz + Cz^2 \tag{10}$$

The far field divergence θ_e (half angle) and the beam waist radius $w_{0,e}$ can be calculated from:

$$\theta_e = \sqrt{C}$$
$$w_{0,e} = \sqrt{A - \frac{B^2}{4C}} \tag{11}$$

This results in a M_e^2 value, given by :

$$M_e^2 = \frac{\pi\theta_e w_{0,e}}{\lambda} \tag{12}$$

Using the definition of the beam radius according to the second order moments of the intensity distribution of the transverse beam profile, the measured values w_e differ from the "real" beam radius w. Therefore, to obtain the M^2 defined by using second order moments, M_e^2 has to be corrected using the following formula (from ISO 11146:1999):

$$M^2 = \left[0.81\left(\sqrt{M_e^2} - 1\right) + 1\right]^2 \tag{13}$$

The similar correction should be done to obtain the second order moment-defined w_0, from the knife edge measured $w_{0,e}$:

$$w_0 = w_{0,e}\frac{1}{\sqrt{M_e^2}}\left[0.81\left(\sqrt{M_e^2} - 1\right) + 1\right] \quad \text{.........} \tag{14}$$

Fig. 4 shows an example of measuring the beam spot size (on x and y) versus the longitudinal coordinate z. The CCD camera initial position is at $z=0$, located on the right side of the beam waist, after the second lens of Fig. 3. The parabolic fit corresponds to the longitudinal beam profile on the right side of the waist. The measurements are for a single mode fiber of 2 m length.

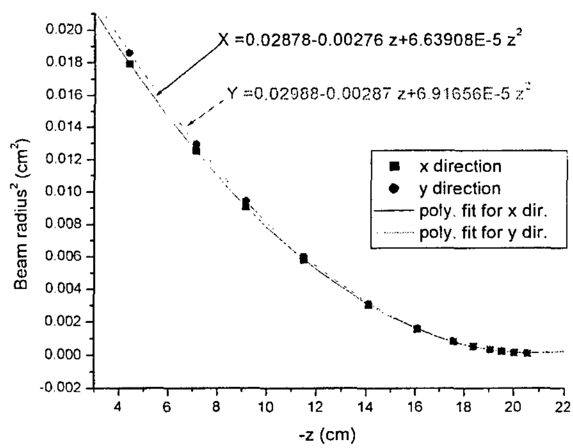

Fig. 4 Dependence of the beam radius versus distance for a single mode fiber (L = 2 m)

The inferred M-squared values were $M_x^2 = 2$ and $M_Y^2 = 2.1$, respectively.

The output from the single mode fiber was observed to exhibit a relatively "clean" mode profile, with a predominantly-circular TEM_{00} type of mode profile (See Fig. 5 below).

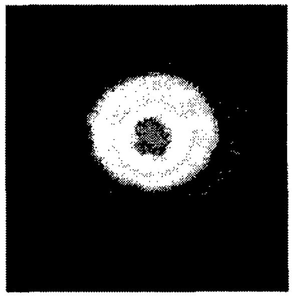

Fig. 5 The output from the single mode fiber observed on a CCD camera

The spot size diameter on the single mode fiber end face, d, can be obtained from the focal lengths of the lenses used (f_1 and f_2) and the diameter of the beam waist after the second lens d_0, as:

$$d = \frac{4\lambda f_1}{\pi}\left[\frac{M^2}{\frac{4\lambda M^2}{\pi}\left(\frac{f_2}{d_0}\right) - f_1\left(\frac{d_0}{f_2}\right)}\right] \tag{15}$$

with $d = 2w$ of Eq. (5).

Using the M^2 value and the d_0 value, the beam diameter on the single mode fiber end face was calculated from Eqs. (13)-(15), to be d = 30 μm. By comparing this result with the single mode fiber core diameter of 8 μm, we infer that inside the single mode fiber the mode is extended beyond the core into the cladding.

5. RESULTS FROM THE MODEL AND COMPARISON WITH EXPERIMENT

For the butt coupled geometry (Fig. 1), using a spot size diameter d = 30 μm (on the single mode fiber end) as input into the multimode fiber, the effective mode diameter in the multimode fiber obtained is : $D = 2\sqrt{\overline{r^2}} = 20.6$ μm.

The number of possible modes into the 50 μm multimode fiber is 100 (computed from the V-number); however, the calculations show that almost all the light coupled into guided modes resides in the four lowest-order modes. The power in guided modes found from our model is illustrated in the following table 1.

TABLE 1

Radial mode index	Percentage of power
n = 0	43%
n = 1	24%
n = 2	3%
n = 3	0.2%

The total power in the four modes is 70.25%. The remaining power goes into leaky and/or radiation modes because of the large spot size input.
The dependence of the theoretical reflectivity and experimental reflectivity versus input power, for the multimode fiber (D = 50 μm: L = 4.4 km) is illustrated in Fig. 6. The experimental values were corrected taking into account for the losses into the circulator (17%), connector (15%) and the Fresnel losses (4%).

The theoretical curves were calculated using the model presented in this paper, for an effective mode diameter of 20.6 μm (curve T_1) and for the whole core diameter of the fiber, D = 50 μm (curve T_2), according to the plane wave model (Fig. 6).

A good agreement is obtained between the experimental values of the SBS reflectivity and the theoretical curve corresponding to the effective mode diameter. Also the theoretical value for the SBS threshold, 88 mW, obtained with our model, is close to the experimentally determined value, 100 mW.

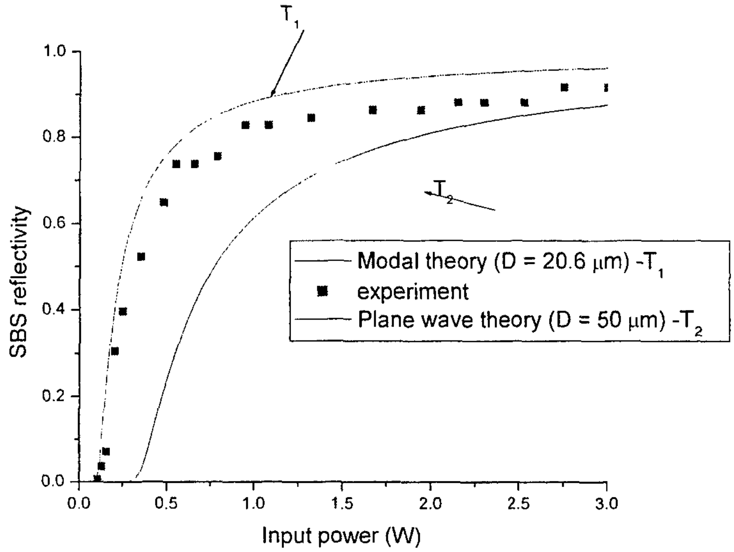

Fig. 6 Dependence of the theoretical reflectivity and experimental reflectivity versus input power, for the multimode fiber (D = 50 μm; L = 4.4 km)

6. CONCLUSIONS

- The usual plane-wave theory of SBS does not correctly predict the threshold when applied to SBS in a multimode fiber: the experimentally determined threshold is 100 mW, while that predicted by the plane-wave theory is 400 mW. The reason for this is that the area illuminated by the input light is not the core area, but "an effective modal area" given by Eq. (9). The model presented here gives good agreement with experiment, as shown in Fig. 6, predicting a threshold of 88 mW.
- Additionally Fig. 6 shows that the SBS reflectivity is high (~92%) indicating good phase conjugation, since most of the input light is returned as Stokes light from the multimode fiber back into the single mode fiber, even with the relatively small number of modes excited into the multimode fiber.

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